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METALLURGICAL EVALUATION OF A NEW ALUMINUM CASTING ALLOY DEVELOPED FOR SPACE VEHICLE USE AT CRYOGENIC TEMPERATURES

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ABSTRACT

The mechanical properties of a new aluminum-copper sand casting alloy were determined at temperatures from 26.7°C (80°F) to -252°C (-423°F). The alloy had high ultimate tensile and yield strengths, as compared to commercial high strength aluminum castings, which increased with a decrease in temperature over the spectrum of 26.7°C to -252.7°C. The percent elongation also increased continually down to -252.7°C. In addition, high toughness (as measured by impact strength at ambient and cryogenic temperatures) characterized the castings examined. Weldments of the alloy to itself and to 2219 aluminum alloy plate were also tested. The alloy appears quite promising for cryogenic applications.

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RESEARCH AND DEVELOPMENT OPERATIONS

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METALLURGICAL EVALUATION OF A NEW ALUMINUM CASTING ALLOY DEVELOPED FOR SPACE VEHICLE USE AT CRYOGENIC TEMPERATURES

SUMMARY

The mechanical properties of three sand castings, representing two heats of a particular alloy composition, were determined at temperatures from 26.7°C (80°F) to -252.7°C (-423°F). The material, an aluminum-copper alloy, had high ultimate tensile and yield strengths which increased with a decrease in temperature over the spectrum of 26.7°C to -252.7°C. The percent elongation also increased continually down to -252.7°C. In addition, high toughness (as measured by impact strength at ambient and cryogenic temperatures) characterized the castings examined.

Weldments of castings-to-plate and of castings-to-castings were made by the automatic and manual TIG processes, respectively. Joints of castings that were automatically TIG welded to aluminum alloy 2219 plate had high tensile strengths in the as-welded condition at ambient and cryogenic temperatures. Castings which were welded manually had only moderate strength in the as-welded condition. However, post-weld heat treatment almost doubled the strength. For cryogenic temperature applications, where high resistance to failure under dynamic loads is required, and for applications where welding is required, the alloy is superior to alloys Tens-50, A-356, and Almag 35.

INTRODUCTION

In most of our current space vehicle structures, aluminum forgings and welded components, which are costly and usually require extensive machining, are used in many instances where a casting would be ideal. Suitable castings must have high strength and toughness and must be compatible with the adjoining aluminum alloy structure. A commercial casting alloy having optimum properties for these requirements has not been available.

This investigation was undertaken to evaluate the characteristics of a new casting alloy which was developed to satisfy the requirements of high strength and toughness for cryogenic applications. The alloy weighs 0.0995 pounds per cubic inch, and its composition falls within these limits:

TABLE I

ALUMINUM ALLOY COMPOSITION LIMITS AND ANALYSIS OF SAND CASTINGS

Copper	3.90 - 4.50
Cadmium	.08 - .12
Magnesium	.06 - .10
Titanium	.02 - .05
Others (Si, Fe, Mn, Cr, Zn, V)	.029 Max. total
Aluminum	Remainder

In this investigation, the tensile characteristics of castings and weldments were studied at temperatures of 26.7°C (80°F), -73.4°C (-100°F), -129°C (-200°F), -196°C (-320°F), and -252.7°C (-423°F). Impact strengths were determined at 26.7°C (80°F), -196°C (-320°F), and -252.7°C (-423°F). Macrostructures, microstructures, and the effects of cast structure defects were included in the studies. The alloy was one of several developed at Battelle Memorial Institute under the technical direction of the author. The research and development program was recently completed under Contract NAS8-1689.

ACKNOWLEDGMENT

The contributions of Messrs. D. N. Williams, R. A. Wood, and H. R. Ogden of Battelle Memorial Institute are gratefully acknowledged. The author also wishes to express his appreciation to the following individuals of the Materials Division, Propulsion and Vehicle Engineering Laboratory: Messrs. D. R. Hamilton and J. H. Arnold for the spectrographic and wet chemical analysis and Messrs. C. McNeil, W. R. Morgan, and J. R. Sandlin for their assistance in the experimental work and in the preparation of the illustrations.

EXPERIMENTAL PROCEDURE

Materials

Three sand castings of the newly developed alloy were used in this evaluation. Butt weldments of the new alloy to 3/8-inch thick 2219-T87 aluminum alloy plate and of casting-to-casting made by the TIG process were also evaluated. All welds were made with 2319 filler wire. The castings, as received, are shown in FIG 1 and 2. The chemical compositions of the test materials are listed in Table I and Table II. The compositions of three other casting alloys that are used currently in space vehicle systems are also listed for comparison in Table II. The chemical compositions of the commercial alloys are within the limits of applicable specifications (Ref. 1).

Radiographs showing casting defects are shown in FIG 3. Porosity and shrinkage were more severe in the castings of heat 64 than in heat 57. Heat 64 was made after heat 57, which indicates that foundry procedures necessary for optimum casting quality were not realized. The melting records of these castings have been reported (Ref. 2).

The macrographic structures of the three test castings of heats 57 and 64 are shown in FIG 4, 5, and 6. The castings of heat 64 had more segregation and shrinkage cracks than heat 57, particularly in the spoke section. The extremely coarse grain texture and the complete absence of columnar or dendritic structure are typical characteristics of the new casting alloy.

Procedure

Tensile tests and Charpy "V" notch impact tests were made at temperatures from 26.7°C (80°F) to -252.7°C (-423°F). Specimens from the castings were taken from both the thin wall and heavy flange section with the exception of the Charpy "V" notch specimens, which were tested from the heavy flange section only. In addition, tensile tests were made from 26.7°C (80°F) to -252.7°C (-423°F) on casting-to-plate weldments and at ambient temperature on casting-to-casting weldments. The test specimen configurations are shown in FIG 7.

The tensile and impact specimens were sampled from the castings at the locations shown in FIG 8. For tensile tests at cryogenic temperatures, specially constructed cryostats and extensometer adapters were used with test procedures developed for these temperatures (Ref. 3). Impact tests at liquid nitrogen and liquid hydrogen temperatures were made with the apparatus shown in FIG 9. The impact fixture was precooled with liquid nitrogen before testing was started. The specimens were immersed in liquid nitrogen and allowed to stabilize at temperature before being transferred to the testing machine. Liquid helium was used in tests to simulate the liquid hydrogen temperature and was supplied from a 50-liter dewar through the vacuum jacketed transfer tube when the solenoid valve was energized. A copper-constantan thermocouple which contacted the impact test specimen under spring-tension just below the point of impact permitted an accuracy of the specimen temperature at impact of $\pm 1°C$ (1.8°F)

Test specimens for the cryogenic mechanical properties determination of the casting-to-plate weldments were made by welding the broken impact test specimens to 3/8-inch thick plate of 2219-T87 aluminum. The material was chemically cleaned, and the joint surfaces were hand-scraped to remove excessive oxides before welding. The casting specimens and aluminum plate were squarely butted and clamped in place on a grooved copper backup bar. The joint was welded by the automatic TIG process with two passes, one on each side of the joint. The filler wire was 1/16-inch diameter 2319 aluminum. A sketch describing the casting-to-plate weldment is shown in FIG 10.

Other weld test specimens that were evaluated at room temperature were made from two sections of castings which were machined for a square butt joint. The joint surfaces were prepared in a manner similar to that used for the casting-to-plate joint. Copper backup tooling was not used. The joint was TIG welded manually with one pass, using 3/32-inch diameter 2319 filler wire. A sketch describing the casting-to-casting weldment is shown in FIG 11.

RESULTS AND DISCUSSION

Tensile Properties

The tensile properties of the three aluminum alloy sand castings are shown in Table III and FIG 12. In all three castings, the tensile and yield strengths increased with decreasing temperature. The elongation, percent in 4D, did not appear to change much at temperatures as low as that of liquid nitrogen. However, a significant increase of elongation was observed at liquid hydrogen temperature.

Of the three castings tested, casting 57-2 had the best overall tensile properties. Castings 64-1 and 64-3 had slightly lower tensile and yield strengths than casting 57-2, particularly at cryogenic temperatures. Casting 64-3 had the poorest properties of the three castings tested. This variation of properties was attributed to inconsistent foundry methods and possible damage caused by improper heat treatment conditions.

Typical stress-strain diagrams and modulus of elasticity at temperatures ranging from ambient to liquid hydrogen are shown in FIG 13 and 14, respectively. The curves represent average values of three sand castings in the -T6 condition.

Microstructure

The microstructures of sand casting 57-2 are shown in FIG 15. These micrographs show large grains of various shapes with a discontinuous network of microconstituents along the grain boundaries. Dispersal of $CuAl_2$ particles occurred randomly throughout the matrix and grain boundaries. Dislocations that were apparent in some of the grains were attributed to internal stresses introduced during tensile loading.

The microstructures of sand castings 64-1 and 64-3 are shown in FIG 16. Segregation of microconstituents could probably be minimized by improving foundry methods and procedures. Gas porosity and microshrinkage were generally excessive.

Impact Properties

The low temperature impact properties of the three castings are listed in Table IV and are shown in FIG 17. In all three castings, the impact strength increased to an apparent maximum value at -196°C (-320°F) and then decreased slightly at -252.7°C (-423°F) to an average value greater than that measured at ambient temperature. It was evident that the characteristic toughness, as measured by impact strength, was affected adversely in the castings from heat 64. Foundry methods and/or heat-treatment conditions were again suspected.

Weldments

The weld strengths at low temperatures of the new aluminum alloy sand castings joined to aluminum alloy 2219-T87 (3/8-inch thick) plate are shown in Table V and FIG 18. The average strength of the automatic TIG weldments at ambient temperature was 36, 200 psi and increased with decreasing temperature. A significant increase of weld strength was observed in the temperature range of -129°C (-200°F) to -252.7°C (-423°F) with average values at these two temperatures of 38, 500 psi and 49, 400 psi, respectively.

The weld strengths at ambient temperature of castings joined to castings are shown in Table VI. The average strength was 25, 700 psi in the as-welded condition. Reheat-treatment of a welded test sample almost doubled the strength. The low as-welded strength was attributed to the fact that the hardness of the castings, originally Rockwell B72 to B76, was reduced to an average value of RB 29.5 by the extended time at elevated temperature inherent in the manual welding procedure.

Comparison of Yield Strength and Impact Properties With Those of Several Other Alloys

The yield strength and impact properties of the new aluminum alloy are compared with those of three sand casting alloys which are presently used widely in space vehicles, Tens-50, A-356, and Almag 35, to illustrate the differences in properties among types of aluminum alloy sand castings at cryogenic temperatures. Data for this comparison are from previous investigations (Ref. 4) and from experimental work supplementary to the early programs related to the development of the new aluminum casting alloy (Ref. 5). This comparison was made on the average yield strength at room temperature and on the impact strength at liquid nitrogen temperature of aluminum alloys that were sand-cast without chills and heat treated with the exception of Almag 35, which is normally a non-heat-treatable alloy.

On the basis of the data shown in FIG 19, the new aluminum alloy was markedly superior in tensile yield strength and toughness, measured by impact strength at -196°C, to the other three commercial aluminum alloys.

CONCLUSIONS

Based on the mechanical property results from a limited number of castings, this new alloy is extremely promising for applications at cryogenic temperatures where high resistance to failure under dynamic loads is desired. In this respect, the alloy is superior to other high strength casting alloys such as Tens-50, A-356, and Almag 35. The alloy is readily weldable and is also heat-treatable.

Foundry methods and procedures used in making the castings were shown to have a definite effect on the low temperature properties; however, like all high strength aluminum castings, close foundry control is necessary. A large commercial heat of this alloy has been ordered, and further evaluation will be made to determine the suitability of the alloy for commercial production.

TABLE II

NOMINAL COMPOSITION OF AUXILIARY MATERIALS [a]

COMPOSITION OF AUXILIARY MATERIALS [c]

Element	2319[e]	2219[e]	A-356	Tens-50	Almag 35[b]
Copper	5.8-6.8	5.8-6.8	0.20	0.20	0.01
Iron	0.30	0.30	0.35	0.40	0.10
Silicon	0.20	0.20	6.50-7.50	7.60-8.60	0.10
Magnesium	0.02	0.02	0.25-0.40	0.40-0.60	7.00
Manganese			0.10	0.20	0.10
Zinc	0.10	0.10	0.10	0.20	
Titanium	0.10-0.20	0.02-0.10	0.20	0.10-0.20	0.10
Vanadium	0.05-0.15	0.05-0.15			
Zirconium	0.10-0.25	0.10-0.25			
Chromium				0.20	
Beryllium	0.0008			0.10-0.30	
Others, Each	0.05	0.05		0.05	
Others, Total	0.15	0.15		0.15	
Aluminum	Remainder	Remainder	Remainder	Remainder	Remainder

(a) Composition given is maximum permissible unless given as a range.

(b) Typical

(c) Composition is in percent of weight.

(e) Composition given in Alcoa Green Letter, Alcoa Aluminum Alloy 2219, Jan. 1962

TABLE III

LOW TEMPERATURE MECHANICAL PROPERTIES OF ALUMINUM ALLOY SAND CASTINGS, -T6 CONDITION [f]

Temperature °C	°F	Specimen[a] No.	U.T.S.[b] ksi	Y.S.[c] ksi	Elongation % in 4D	Fracture[d] Location
+26.7	+80	57-2-A-1	48.1	45.8	6.0	GL
		57-2-A-2	46.7	44.0	6.0	GL
		57-2-B-3	50.5	48.0	5.0	GL
		64-1-A-1	47.3	46.0	4.0	GL
		64-1-B-2	46.6	44.6	4.0	GL
		64-1-B-3	50.6	49.7	4.0	GL
		64-3-A-1	44.5	39.4	5.0	GL
		64-3-A-2	46.7	40.2	7.0	GL
		64-3-B-3	48.2	45.0	4.0	GL
		Average	47.7	44.7	5.0	
-73.4	-100	57-2-A-4	49.5	48.6	5.0	OEG
		57-2-A-5	51.3	49.9	5.5	GL
		57-2-B-6	53.9	52.5	4.0	GL
		64-1-A-4	48.1	48.1	2.0	GL
		64-1-B-5	50.8	49.3	4.0	GL
		64-1-B-6	50.5	48.0	3.0	GL
		64-3-A-4	43.4	41.2	6.0	GL
		64-3-B-5	47.6	44.2	-	OGL
		64-3-B-6	51.4	46.6	5.0	GL
		Average	49.6	47.6	4.3	
-129.0	-200	57-2-A-7	50.9	48.5	4.0	GL
		57-2-B-8	57.5	54.5	4.5	GL
		57-2-B-9	49.9	49.0	4.0	GL
		64-1-A-7	56.9	(e)	6.0	GL
		64-1-A-8	51.7	50.4	-	OGL
		64-3-A-7	43.9	43.6	3.0	GL
		64-3-A-8	48.6	46.2	6.0	GL
		64-3-B-9	47.5	41.9	8.0	GL
		Average	50.9	47.7	5.1	
-196.0	-320	57-2-A-10	59.2	55.2	4.0	OEG
		57-2-A-11	55.8	53.7	6.0	GL
		57-2-B-12	64.4	58.8	6.5	GL
		64-1-A-10	57.0	54.5	-	OGL
		64-1-B-11	58.1	55.7	3.0	GL
		64-1-B-12	59.0	54.6	5.0	GL
		64-3-A-10	51.7	44.8	9.0	GL
		64-3-A-11	51.3	44.6	10.0	GL
		64-3-B-12	52.9	49.9	5.5	GL
		Average	56.6	52.4	6.4	
-252.7	-423	57-2-A-13	70.2	63.3	6.5	EC
		57-2-A-14	72.9	61.5	7.0	EC
		57-2-B-15	71.3	(e)	-	OGL
		64-1-A-13	65.4	55.0	7.0	GL
		64-1-A-14	75.7	56.7	12.0	GL
		64-1-B-15	73.2	(e)	11.0	EC
		64-3-A-13	67.0	51.8	11.0	GL
		64-3-A-14	68.8	52.1	11.0	GL
		64-3-B-15	70.8	57.6	-	OEG
		Average	70.6	56.9	9.4	

(a) Example: 57-2-A-13 means heat 57, casting number 2, test location area "A", test specimen 13.
(b) U.T.S. - Ultimate tensile strength
(c) Y.S. - Yield strength, determined by .2% offset method
(d) EC - Extensometer clamp
OEG - Outside extensometer gage length
GL - Gage length
OGL - Outside gage length
(e) Malfunction of extensometer prevented determination of yield strength.
(f) -T6 condition was within Rockwell hardness range (RB) 72 to 76.

TABLE IV

LOW TEMPERATURE CHARPY V-NOTCH IMPACT PROPERTIES OF ALUMINUM ALLOY SAND CASTINGS

	CHARPY IMPACT PROPERTIES, Ft-Lb.		
Casting*	+26.7°C (+80°F)	-196°C (-320°F)	-252°C (-423°F)
57-2	14.0	25.0	21.5
57-2	18.3	17.8	18.3
64-1	9.8	12.3	14.8
64-1	11.5	18.5	11.0
64-1	-	-	15.0
64-3	14.3	16.8	14.5
64-3	-	21.0	16.0
64-3	-	-	13.0
64-3	-	-	16.8
64-3	-	-	14.3
Average	13.6	18.6	15.5

* 57-2 means heat number 57, casting number 2.

64-1, 64-3 means heat number 64, casting 1 and 3, respectively.

TABLE V

WELD STRENGTHS AT LOW TEMPERATURES OF ALUMINUM ALLOY SAND CASTINGS JOINED TO 2219-T87 PLATE, AUTOMATIC TIG WELDED WITH 2319 FILLER, AS-WELDED CONDITION

Temperature °C	°F	Specimen No. (*)	Ultimate Tensile Strength psi
+26.7	+80	57-2-1	33,500
		57-2-2	37,000
		57-2-3	37,200
		57-2-4	35,700
		64-1-1	36,600
		64-1-2	36,100
		64-1-3	38,000
		64-3-1	34,000
		64-3-2	36,500
		64-3-3	37,200
		64-3-4	37,900
		Average	36,200
-73.4	-100	64-1-10	37,700
-129.0	-200	64-3-11	37,500
		64-3-12	40,700
		64-3-13	37,400
		Average	38,500
-196	-320	57-2-5	52,500
		57-2-6	43,300
		64-1-5	37,600
		64-1-6	48,400
		64-1-7	51,300
		64-3-5	40,300
		64-3-6	36,100
		64-3-7	38,300
		Average	43,500
-252.7	-423	57-2-7	49,700
		57-2-8	46,500
		57-2-9	45,000
		64-1-8	49,700
		64-1-9	52,300
		64-3-8	53,600
		64-3-9	50,100
		64-3-10	48,200
		Average	49,400

*Example: 57-2-7 means heat 57, casting number 2, test specimen number 7.

TABLE VI

MANUAL TIG WELD STRENGTHS OF ALUMINUM ALLOY SAND CASTINGS, 2319 FILLER

Castings	Ultimate Tensile Strength psi	Condition
57-2/64-1	26,400	As-welded
	25,000	As-welded
Average	25,700	
57-2/64-1	49,700	T6(*)

(*) Reheat treatment: 40 hours 1000°F ± 3°F
Water quenched,
plus 16 hours 325°F ± 5°F

Prior to reheat treatment, Rockwell hardness of casting, after welding, averaged RB 29.5.

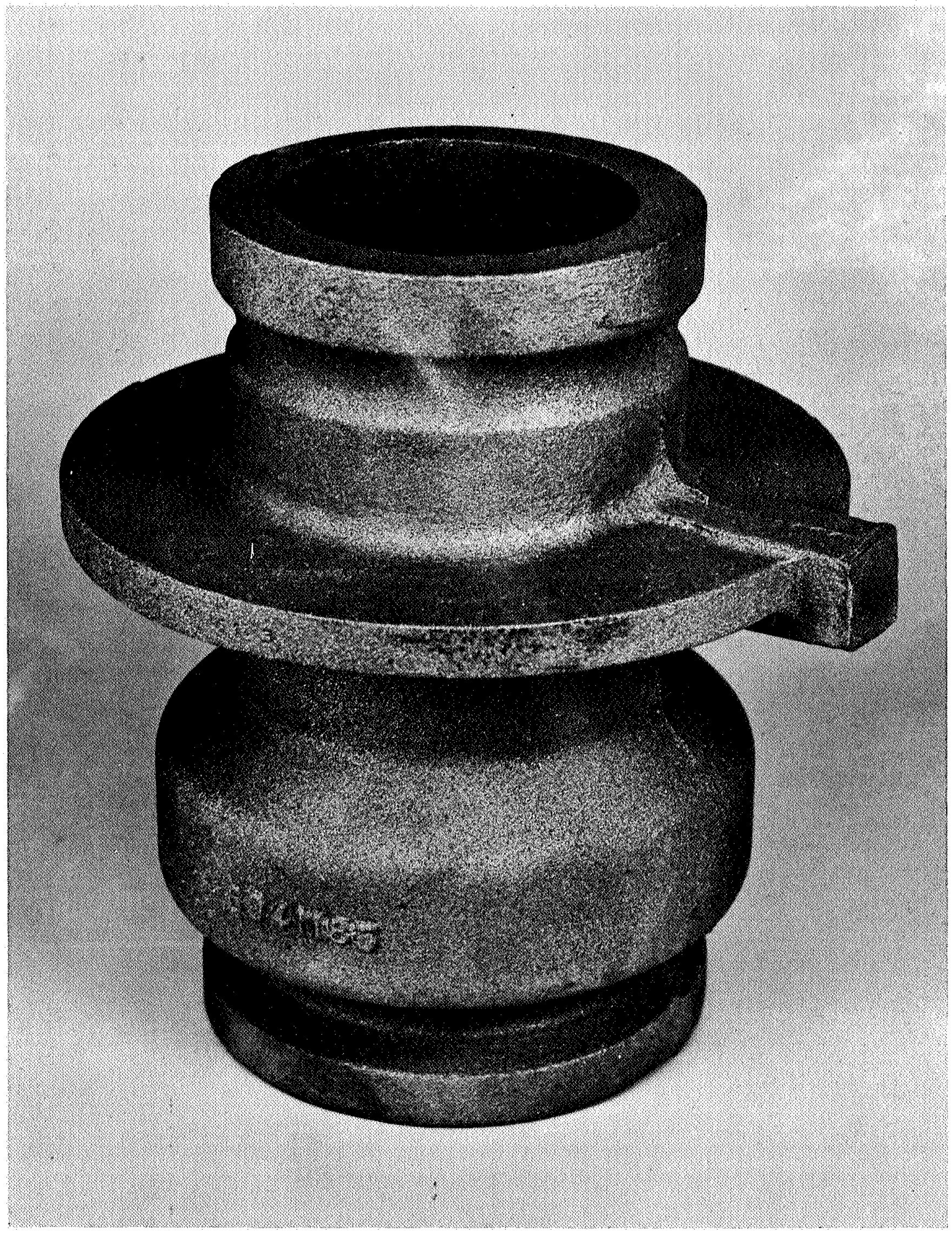


FIGURE 1. Sand Casting, As Received

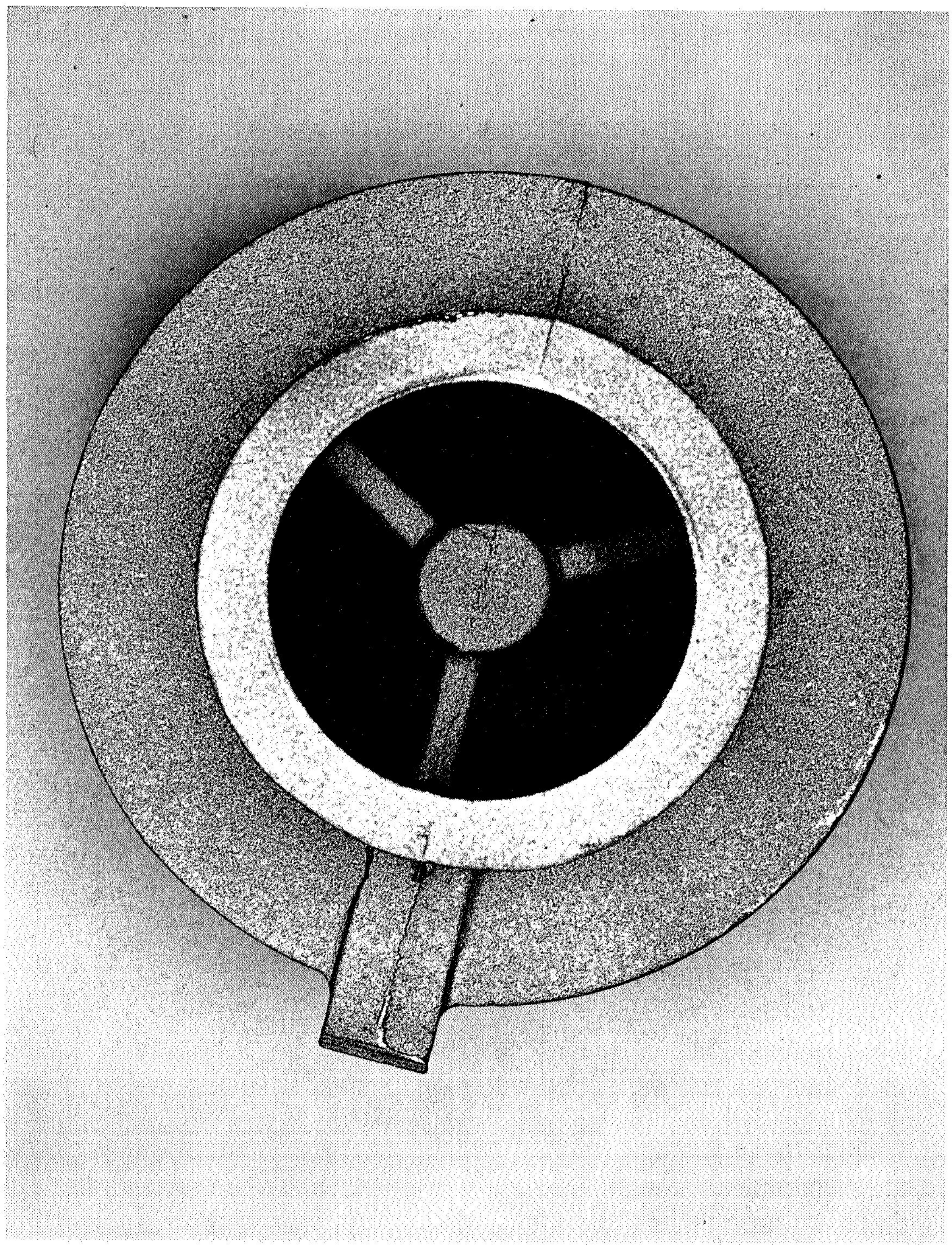
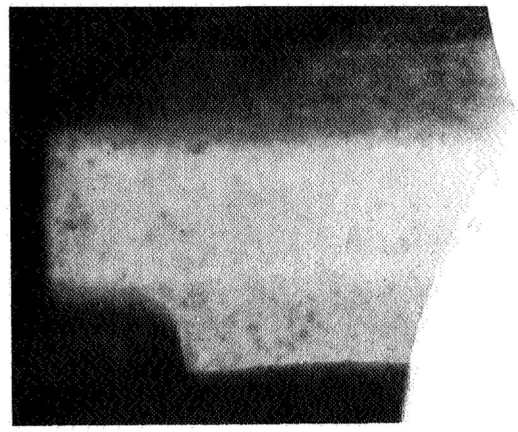
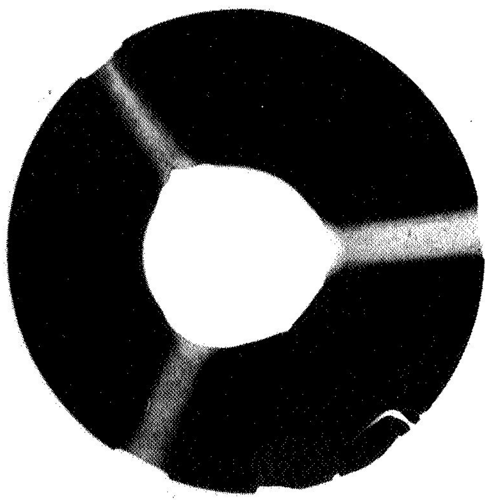


FIGURE 2. Sand Casting, As Received

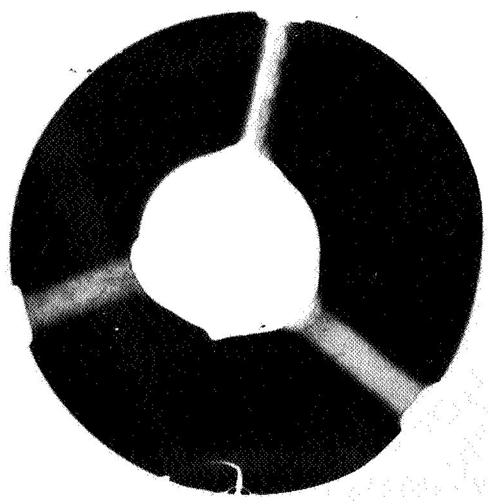
57—2



64—1



57—2



64—3

FIGURE 3. Radiographs Showing Casting Defects

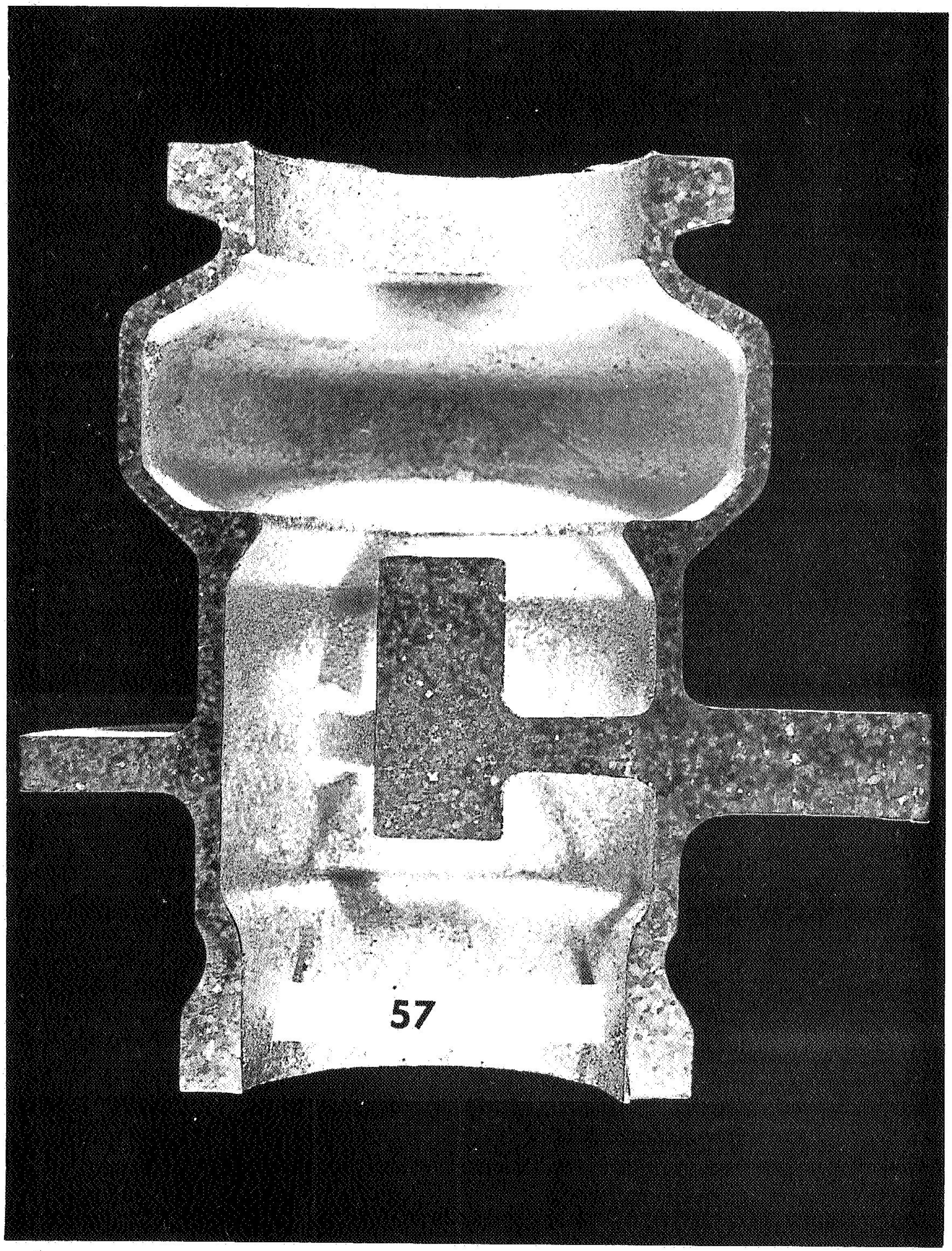


FIGURE 4. Macrograph, Heat 57

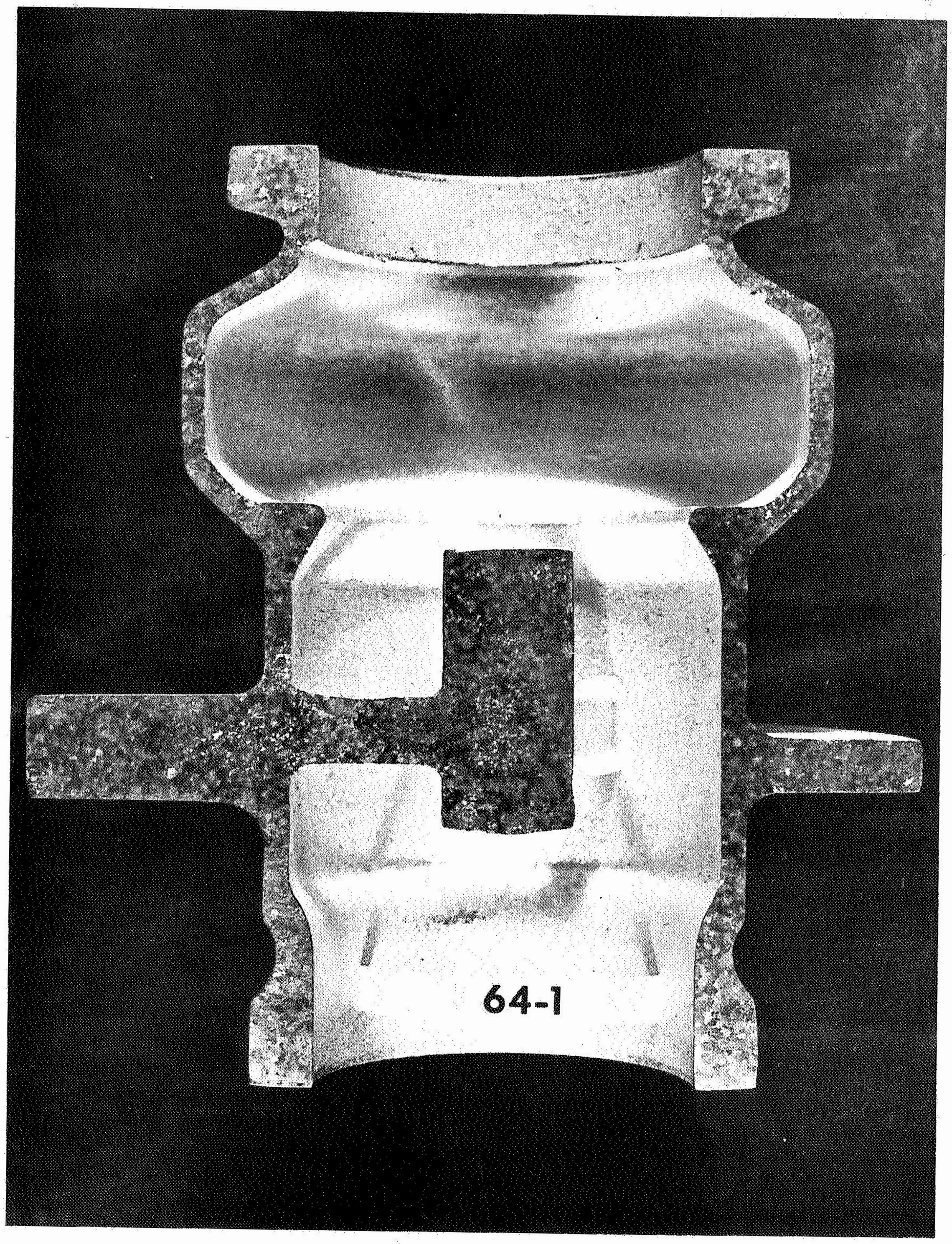


FIGURE 5. Macrograph, Heat 64

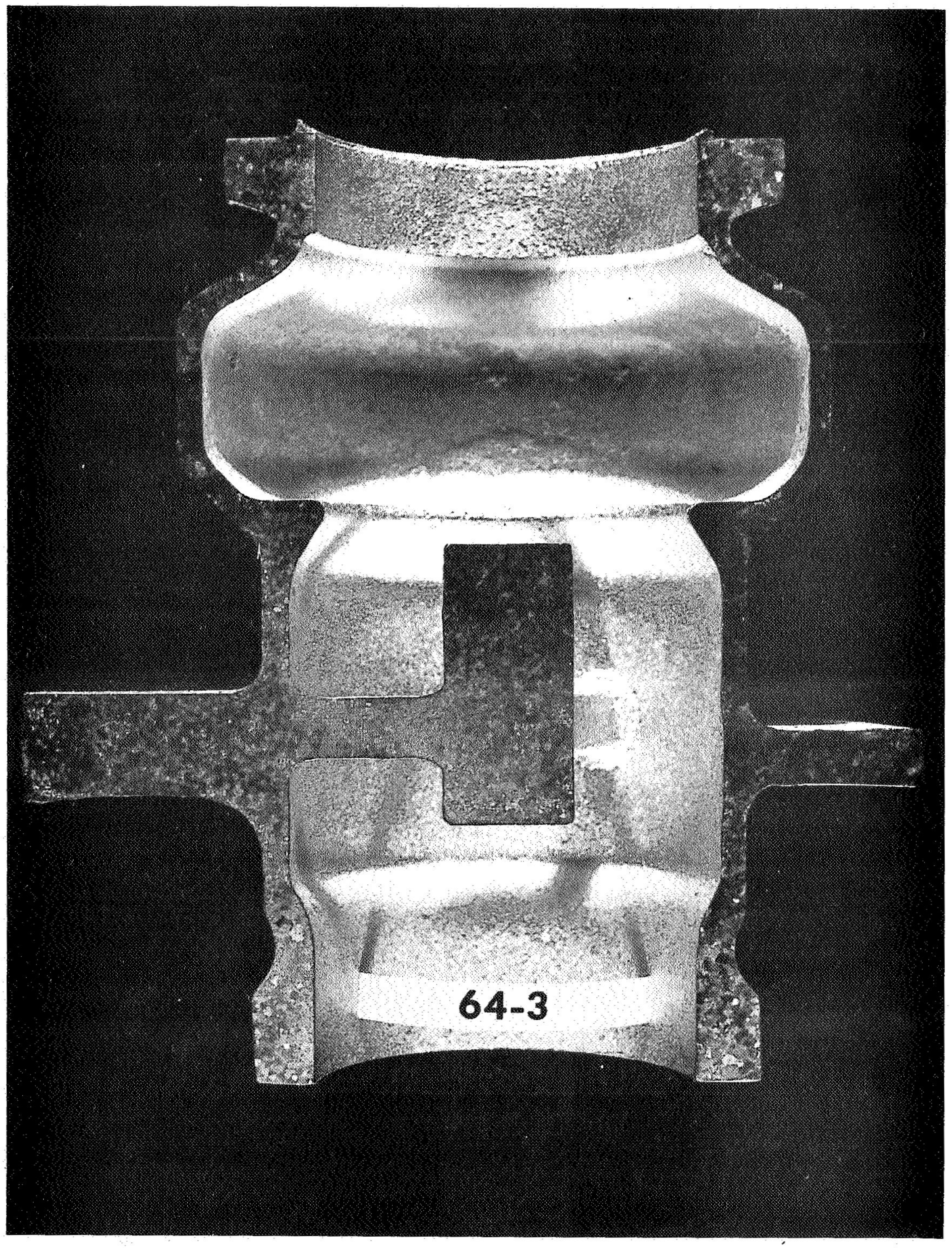
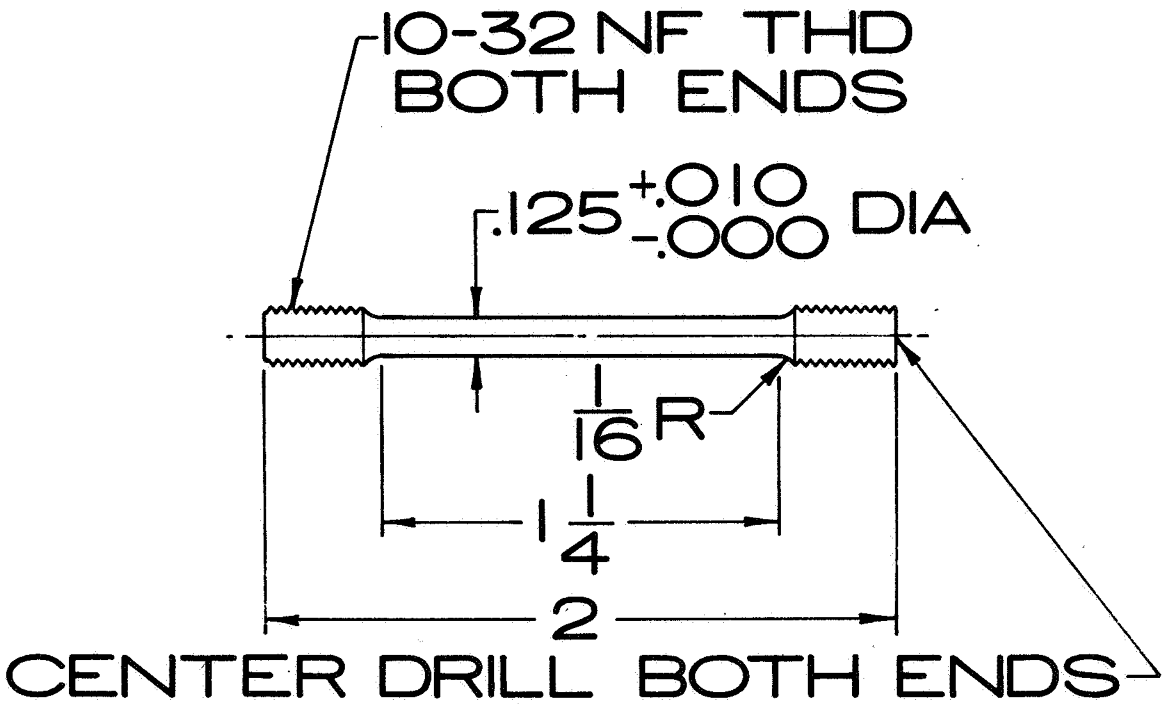
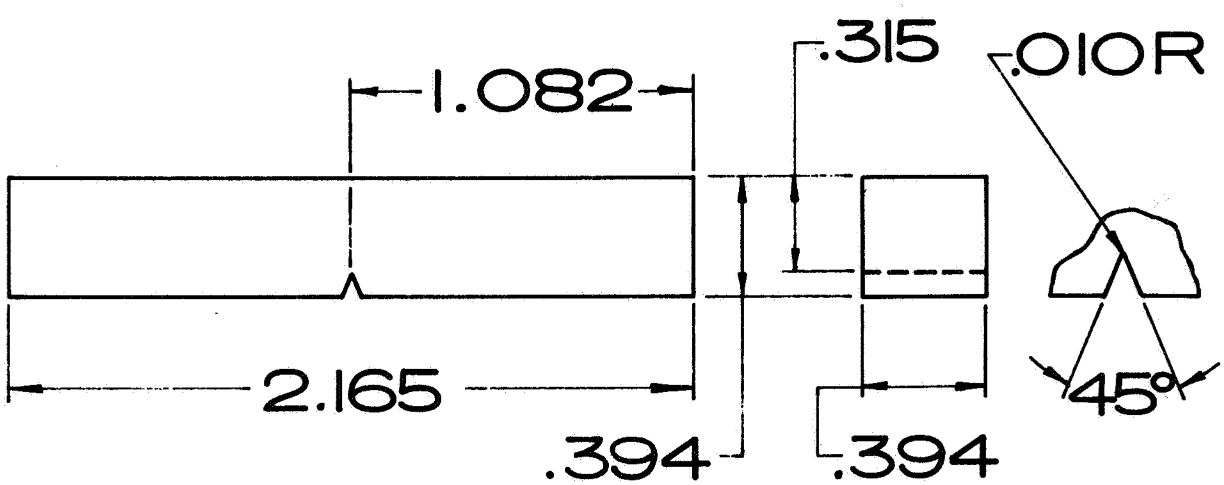


FIGURE 6. Macrograph, Heat 64



TENSILE TEST SPECIMEN



V-NOTCHED CHARPY SPECIMEN

FIGURE 7. Test Specimens

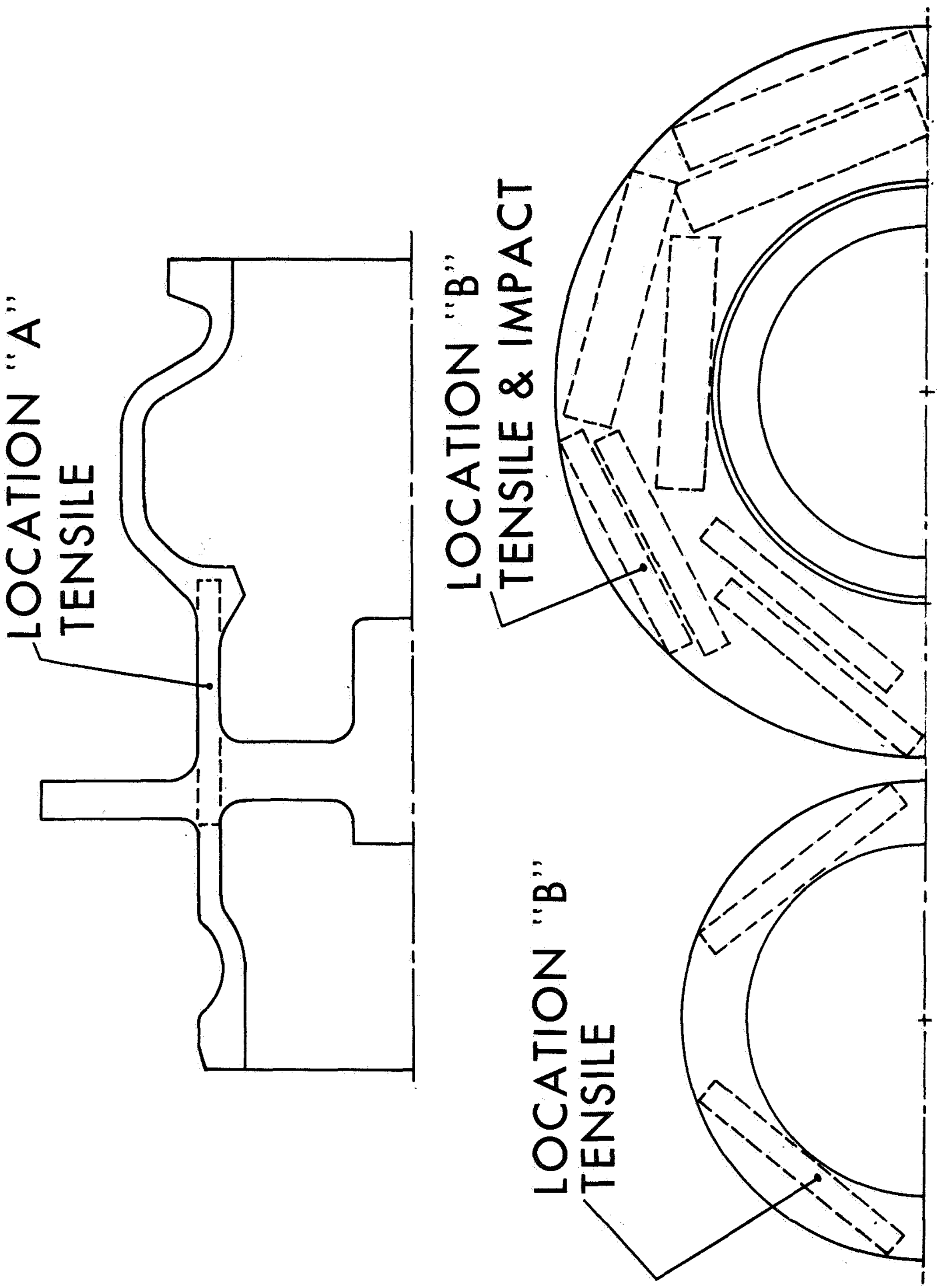


FIGURE 8. Test Specimen Location

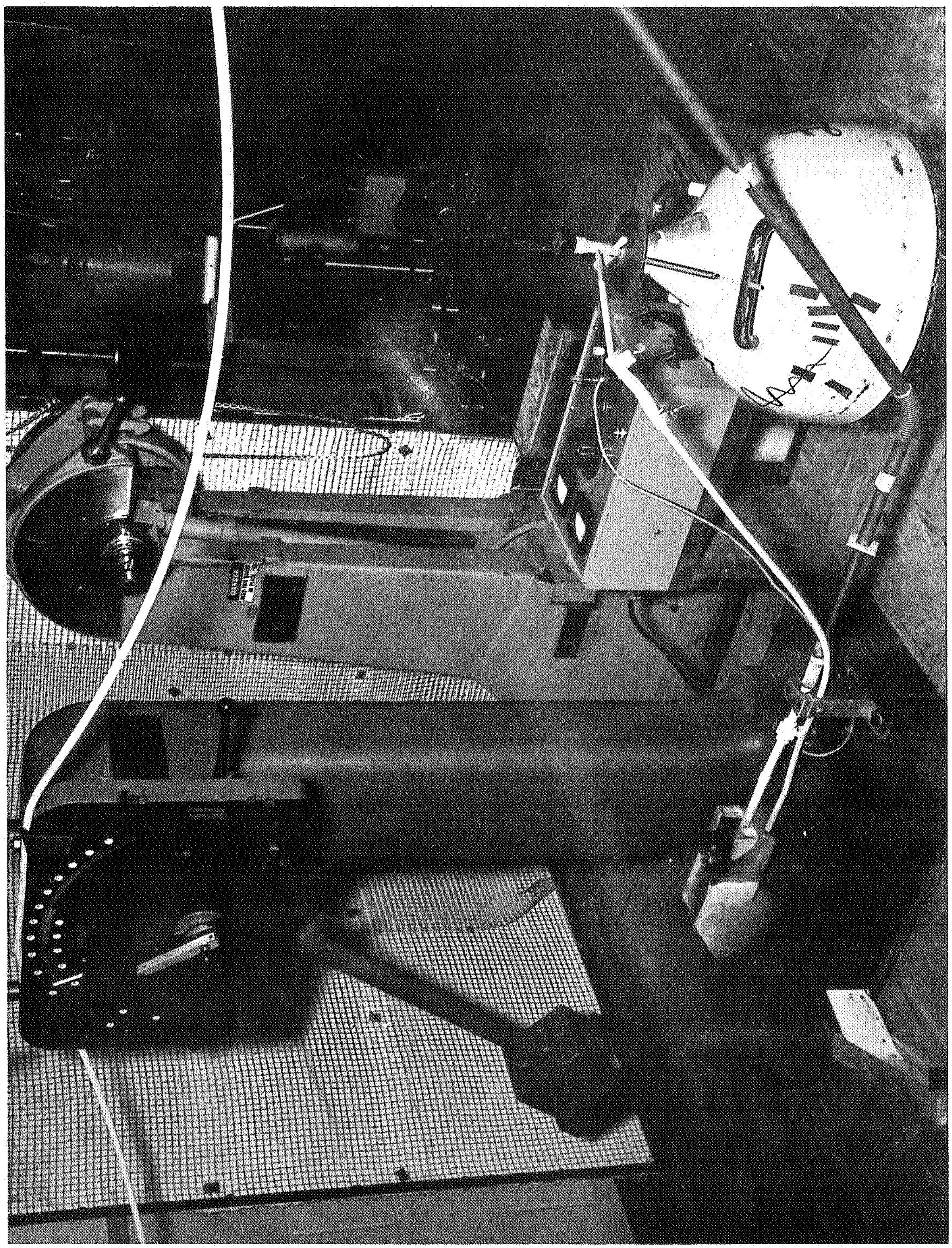


FIGURE 9. Low Temperature Impact Test Apparatus

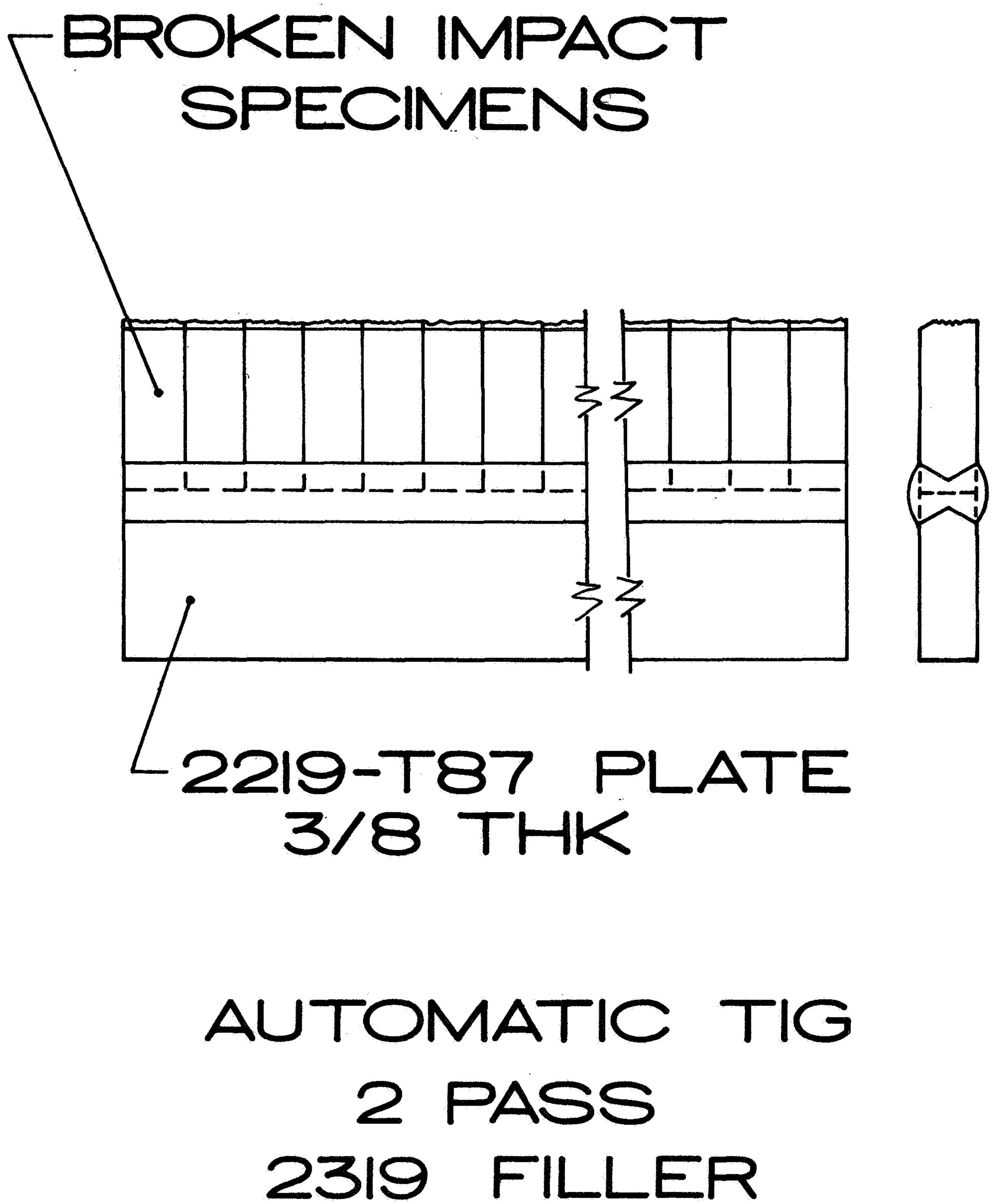


FIGURE 10. Casting-to-Plate Weldment

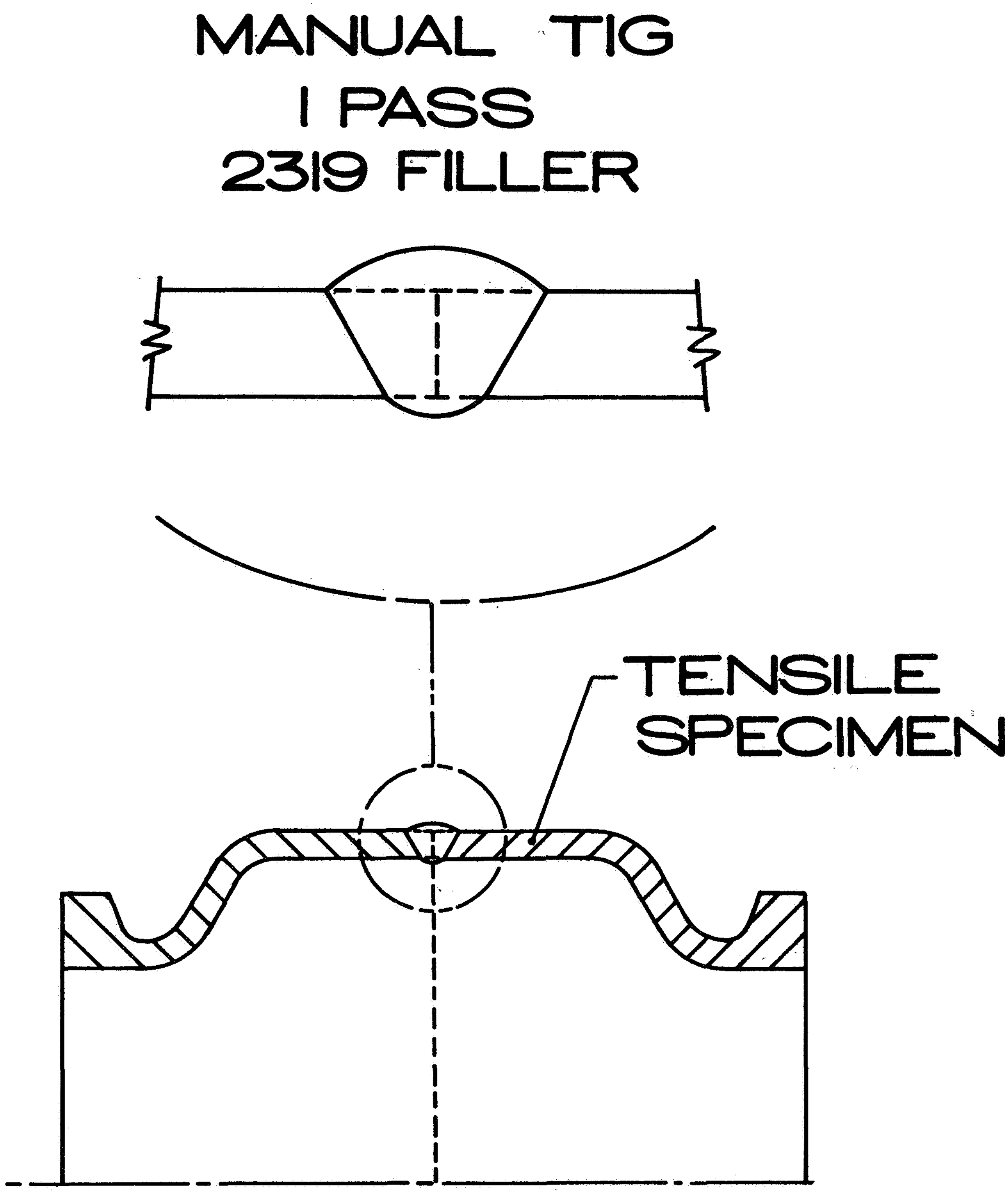


FIGURE 11. Casting Weldment

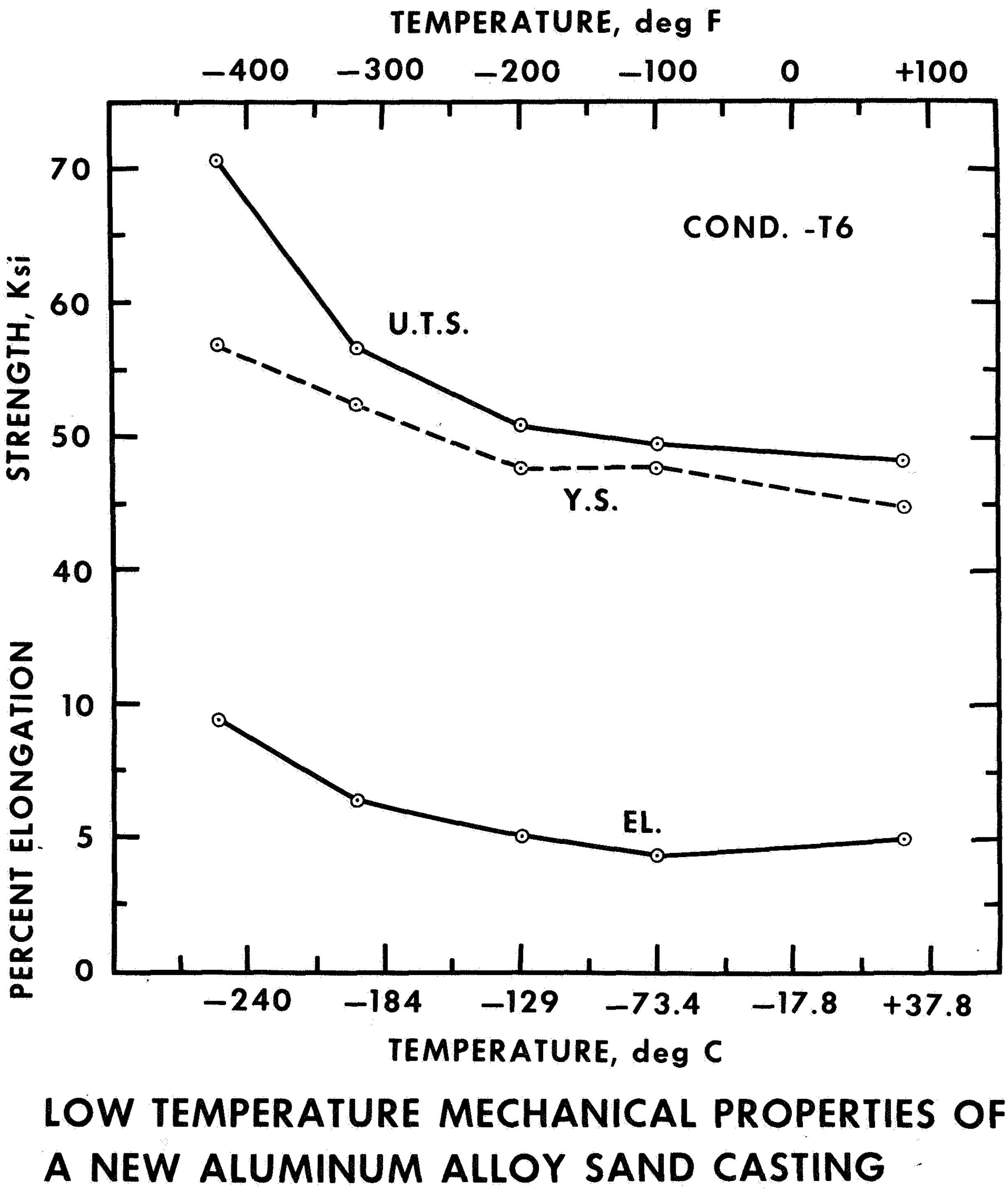
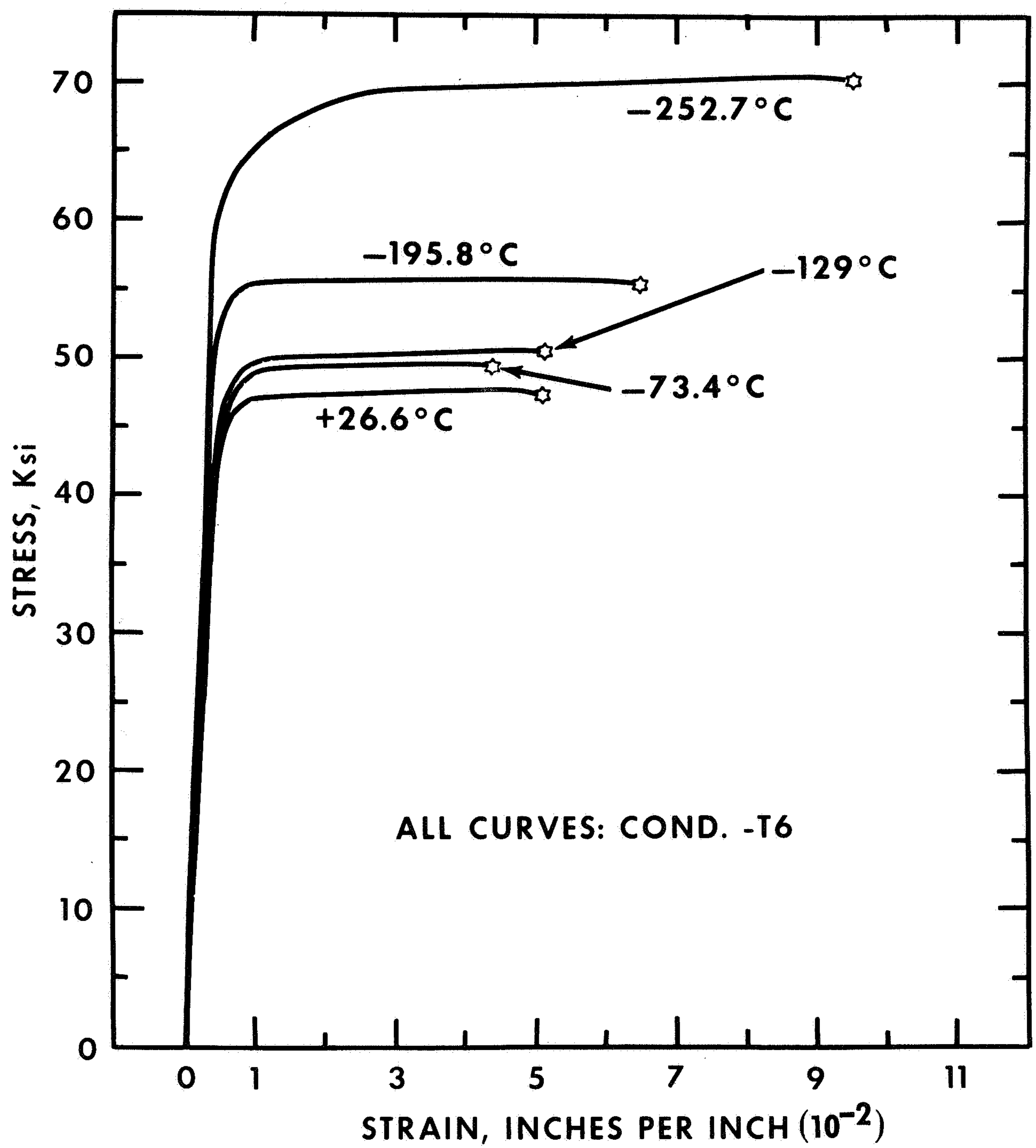


FIGURE 12. Low Temperature Mechanical Properties of a New Aluminum Alloy Sand Casting



STRESS-STRAIN DIAGRAMS OF A NEW ALUMINUM ALLOY SAND CASTING

FIGURE 13. Stress-Strain Diagrams of a New Aluminum Alloy Sand Casting

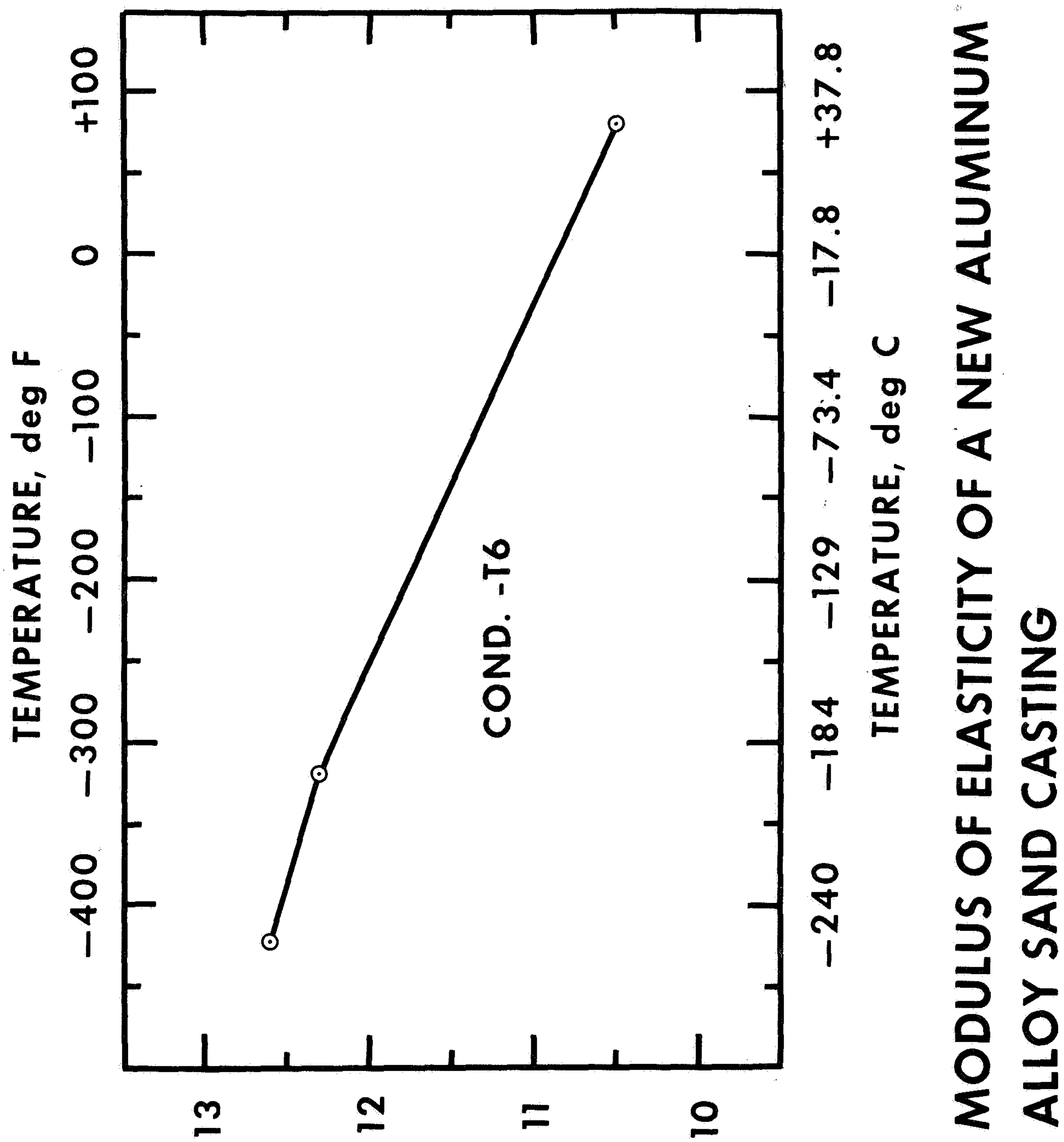


FIGURE 14. Modulus of Elasticity of a New Aluminum Alloy Sand Casting

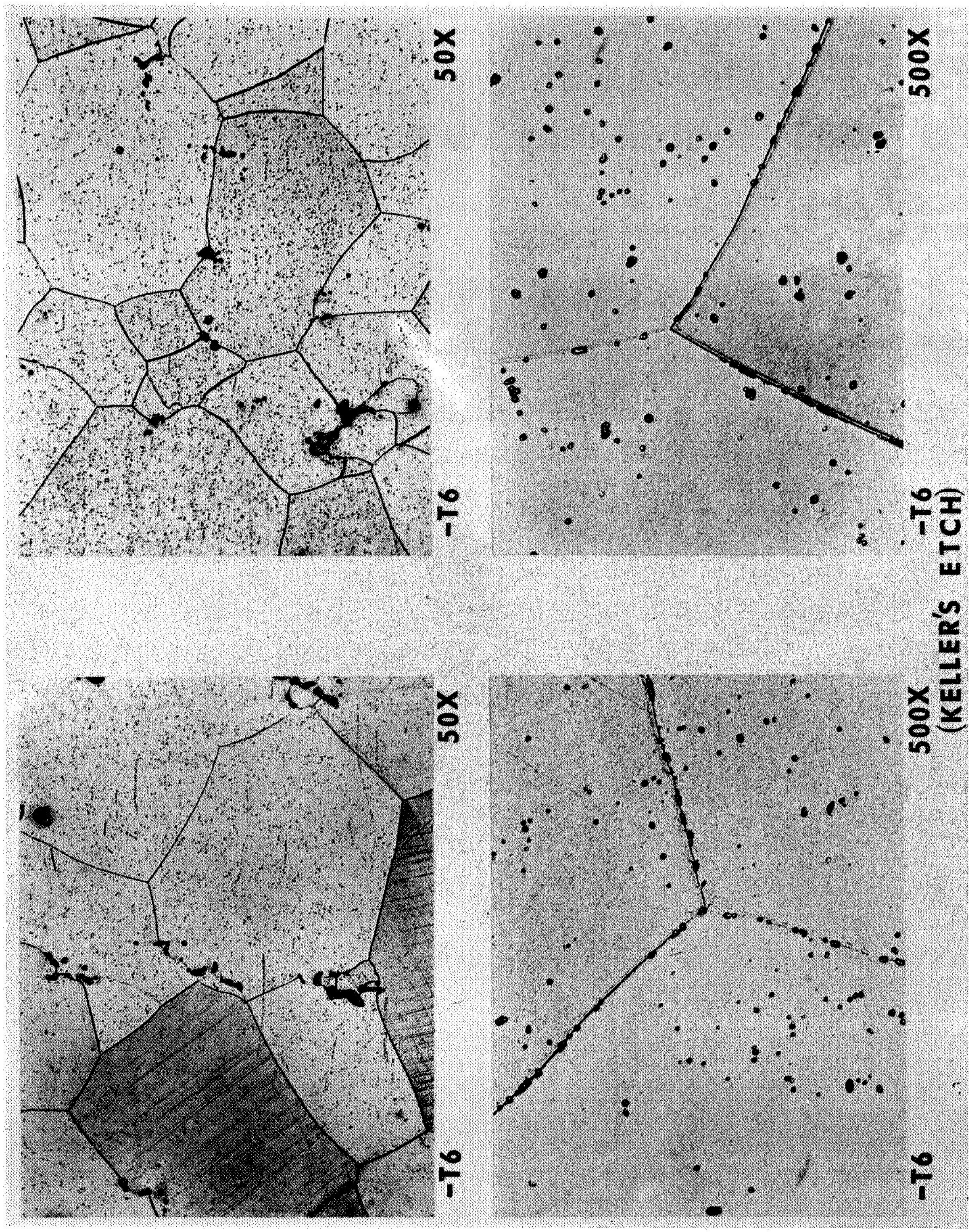


FIGURE 15. Microstructures of Sand Casting 57-2

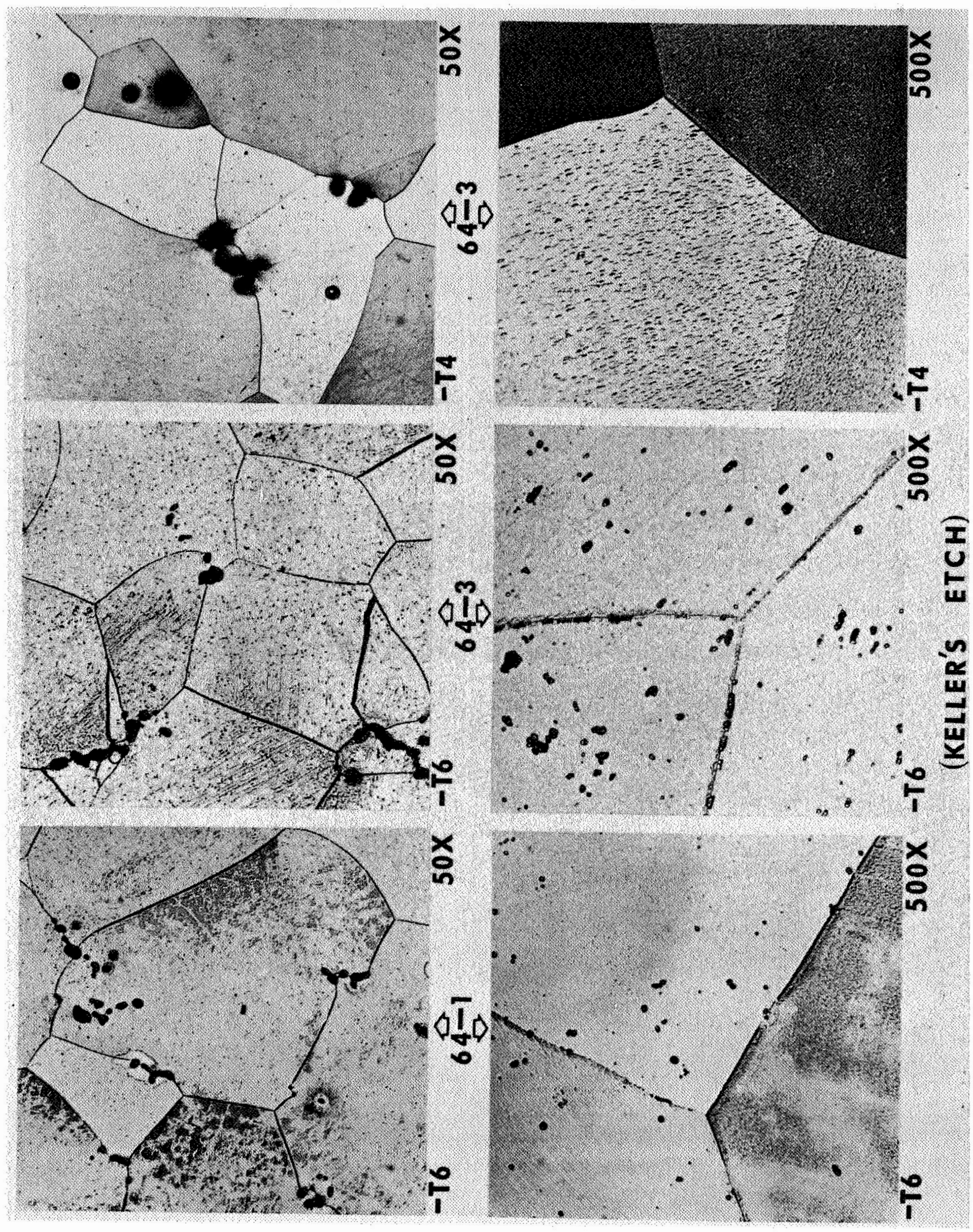


FIGURE 16. Microstructures of Sand Castings 64-1 and 64-3

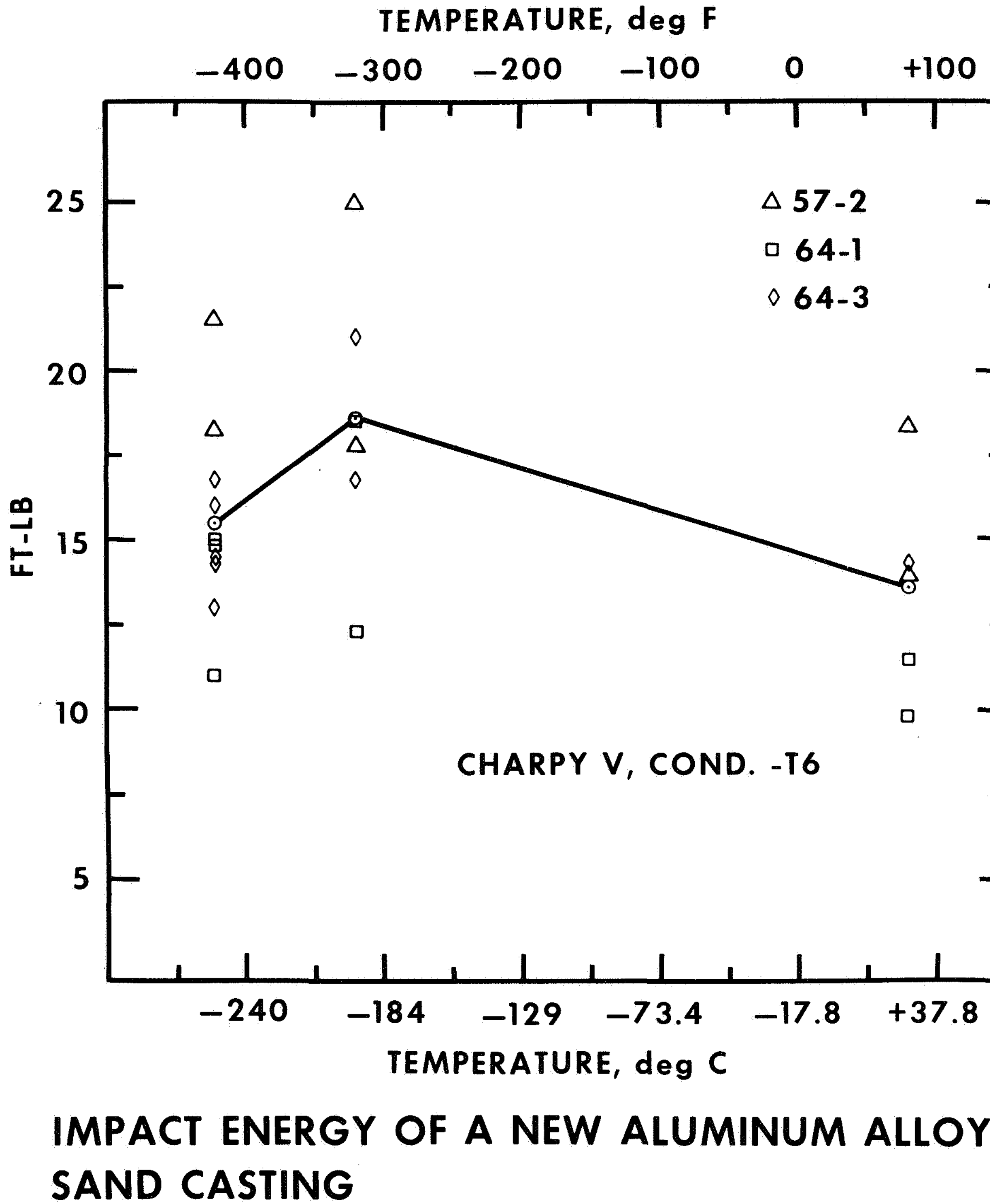
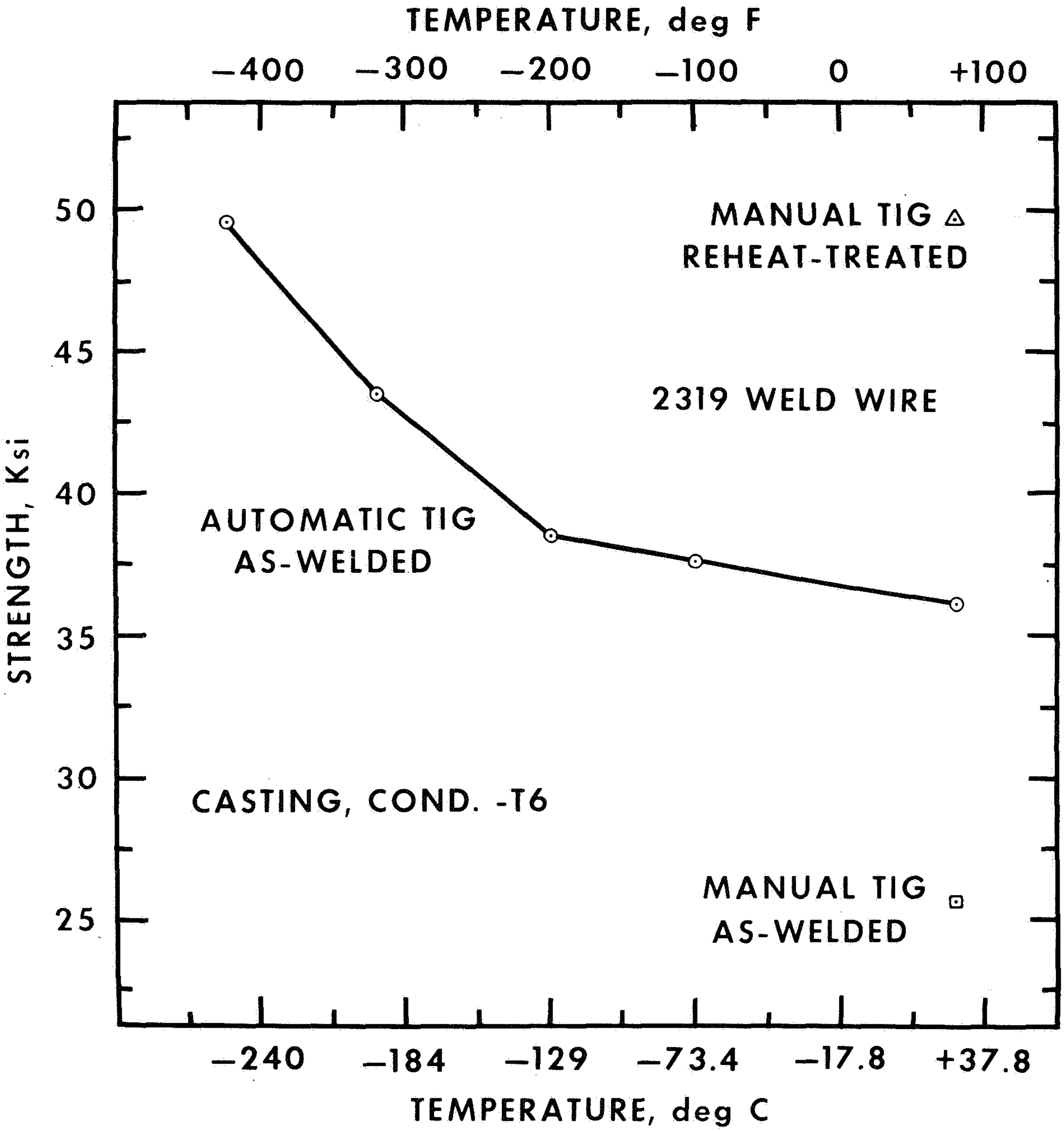
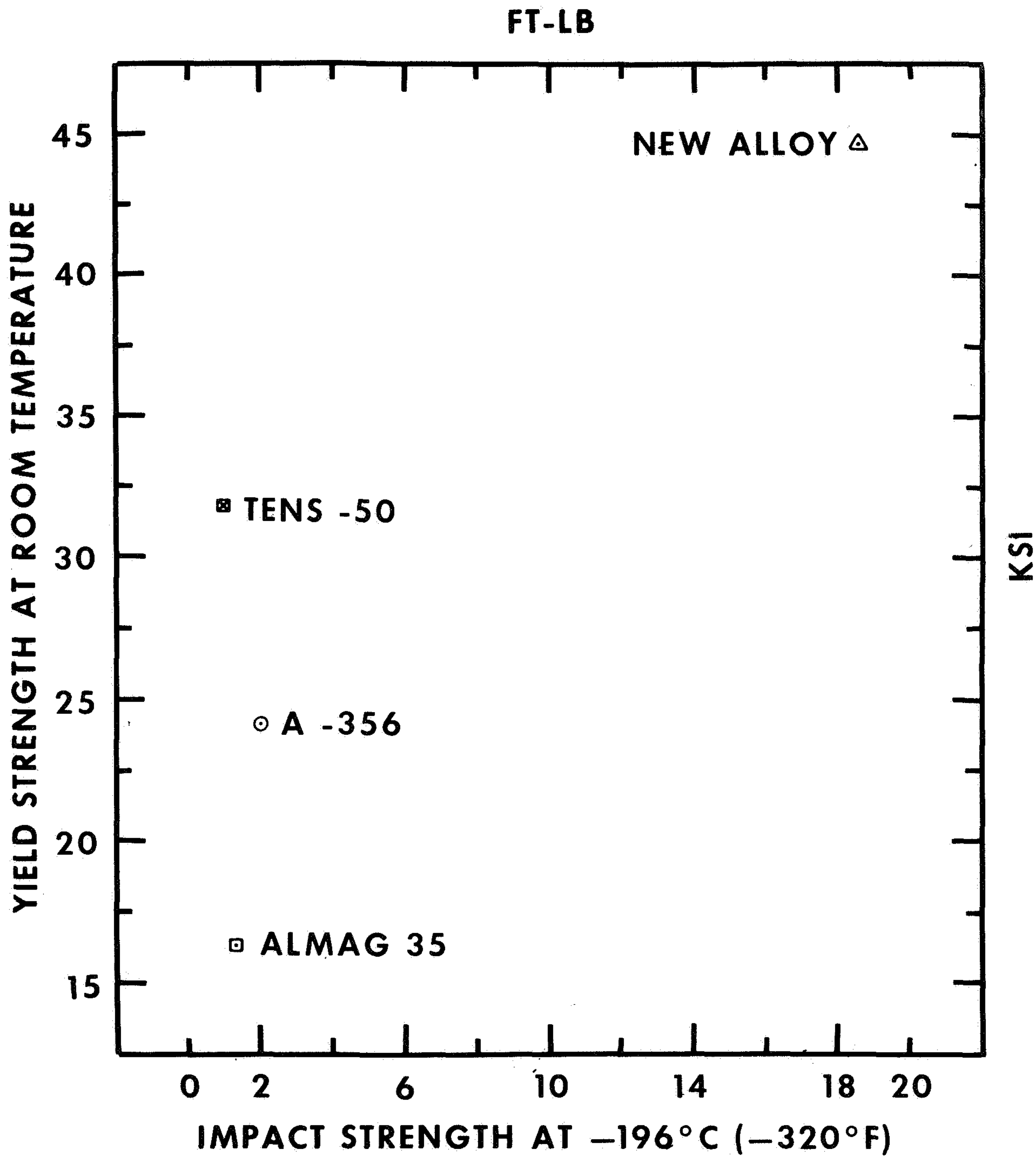


FIGURE 17. Impact Energy of a New Aluminum Alloy Sand Casting



WELD STRENGTHS OF A NEW ALUMINUM ALLOY SAND CASTING

FIGURE 18. Weld Strengths of a New Aluminum Alloy Sand Casting



COMPARISON OF MECHANICAL PROPERTIES OF SEVERAL ALUMINUM ALLOYS, SAND CASTINGS

FIGURE 19. Comparison of Mechanical Properties of Several Aluminum Alloys, Sand Castings

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3. Miller, P. C., "Low Temperature Mechanical Properties of Several Aluminum Alloys and Their Weldments," MTP-S&M-61-16, October 1961.

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5. Williams, D. N., Wood, R. A., and Ogden, H. R., "Development of Aluminum Castings with High Impact Strength at Low Temperatures," Summary Report on Contract NAS8-1689, George C. Marshall Space Flight Center, June 26, 1962.

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METALLURGICAL EVALUATION OF A NEW
ALUMINUM CASTING ALLOY DEVELOPED FOR
SPACE VEHICLE USE AT CRYOGENIC TEMPERATURES

By P. C. Miller

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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